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STUDY OF CURRENTS ALONG THE PT.SUR
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IN FEBRUARY 1989

by

Paul Berryman

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Study of Currents Along the Pt.Sur Transect in February 1989

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY

from the

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ABSTRACT

Ocean currents and density were measured off Point Sur, California in February 1989 using Pegasus (an acoustically tracked velocity profiler), ADCP (a ship-mounted acoustic doppler current profiler), and CTD (conductivity, temperature, depth profiler). Absolute velocities are compared with geostrophy and various flow regimes are analyzed with respect to prominent features and historical and other recent data. Geostrophic cross-sections based on various levels of no motion (LNM) are compared. Temperature, salinity, and density fields are examined and correlated to velocity features.

The California Current is a weak (< 5 cm/s) southeastward flow starting about 60 km from the coast. The Davidson Inshore Current is a strong (> 25 cm/s) surface-intensified core of warm, fresh water centered 30 km offshore, and located in the top 100 m. A subsurface maximum of westward flow exists in a well-defined jet 100 m deep about 30 km off Point Sur. There is a trench jet located along the bottom between the continental slope and a seamount 33 km from the coast, which could either be topographically steered out of Monterey Canyon or recirculated from further offshore. A band of alternating meridional velocity shears is seen in geostrophic sections (based on CTD data) 45-100 km from the coast, not supported by other data, and seems to be located in deep water near the edge of the continental margin. Its position in the water column can be shifted vertically by applying various LNMs, but based on density sections and ADCP data it appears to be a feature limited to the water below 1500 m. Otherwise, a 1000 m level of no motion seems to produce the best cross-section of geostrophic velocity.

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I. INTRODUCTION

The California Current (CC) is the eastern boundary current of the subtropical North Pacific gyre, and extends from Washington to Baja California. Typical of eastern boundary currents, it is a broad, shallow, and weak system of equatorward flow. Velocities are usually less than 25 cm/s, most of the flow is limited to the top 300 m, and the system extends from the coast out to about 900 km with a core 200-300 km offshore [Ref. 1]. Low temperature, low salinity subarctic water originating near the West Wind Drift is carried south and mingles with the other water masses found in the region. These are the eastern North Pacific water mass on the western boundary of the CC, and Equatorial Pacific water from the south.

In addition to the broad equatorward flow, the system is characterized by a poleward undercurrent closer inshore, variously called the Inshore Countercurrent (IC), or the Davidson Inshore Current (DIC) when it reaches the surface. This poleward flow is somewhat stronger, more narrow, and generally found over the continental slope and shelf. While the equatorward flow of the CC is fairly consistent year-round, the countercurrent exhibits strong annual variability, alternately kept at depth in the spring and summer as a result of the strong northwesterly winds, and surfacing in the fall and winter with the relaxation of the winds.

The continental margin off Point Sur consists of a shelf extending some 15 km from the coast to a depth of 150 m, followed by a steeper continental slope out to 75 km, with a gentler rise to the basin floor 3500 meters deep about 100 km offshore. The marine topography off the Central California coast is dramatic, with numerous canyons cut into the continental shelf. The largest of these, the Monterey Canyon, is just north of Point Sur, and probably plays a significant role in the currents there.

The CC has been the subject of numerous studies in the past, from the long-term data collection of CalCOFI (California Cooperative Oceanic Fisheries Investigations) to specific process experiments of recent years such as the Coastal Transition Zone Program [Ref. 2]. The CalCOFI data set represents a forty year record of hydrographic surveys aimed at examining the long-term variability of the coastal region and the environmental impact on local fisheries. An excellent review of the CalCOFI program can be found in the October 1988 CalCOFI Reports [Ref. 3: pp. 42-65]. Velocities were derived from these hydrographic data using an assumed level of no motion (LNM) with

the geostrophic relationship. More recent work, particularly by the Naval Postgraduate School in Monterey, utilizes continuous current profilers which yield velocities directly. Such instruments allow more accurate velocity data to be collected rapidly and with greater ease over large geographic regions, and have largely removed the guesswork associated with erroneous assumptions about levels of "no motion".

The data described here were collected 2-7 February 1989 aboard the *RV Point Sur* as part of an ongoing effort to examine in detail the structure of the California Current. The purpose of this study is to analyze the data from that cruise, interpret and compare the results, and try to gain a comprehensive understanding of the oceanic environment during that period. In particular, I describe the spatial structure of the various currents and jets, and compare geostrophic flow with absolute current measurements. Chapter 2 covers the instruments, methods used, and data processing techniques. Chapter 3 provides detailed analysis of the results obtained. Finally, Chapter 4 is a summary of conclusions and offers some recommendations for future work.

By analyzing data from the first direct continuous current-measuring cruise on the Central California coast in February, this study provides the "first look" at a current regime which has heretofore only been inferred. As such, it may provide valuable guidance to any future winter studies of the California Current, as well as give important clues as to how to interpret historical data.

II. DATA COLLECTION AND PROCESSING

All of the data for this study were collected from 2-7 February 1989 off Point Sur, California. The Naval Postgraduate School surveys bimonthly what is known as the Point Sur Transect. It is a line extending from the coast along 36°20'N about 100 km, then turning southwest along CalCOFI line 67 another 40 km.

Data were collected primarily by three instruments. Pegasus is a free-falling acoustically-tracked Lagrangian drifter which yields pressure, temperature, and horizontal velocity components from the surface to the bottom. A more thorough discussion of this instrument is given by Spain, et al. [Ref. 4]. The ADCP (Acoustic Doppler Current Profiler) is a hull-mounted sonar which gives continuous profiles of all three velocity components from 2 meters below the ships' keel to a nominal working depth of 300-400 meters. The reader is referred to Kosro [Ref. 5] for a complete description of this instrument. The CTD (Conductivity Temperature Depth) unit is lowered from a ship by means of a wire and winch; it measures conductivity, temperature, and pressure continuously, and collects water samples at discrete depths. Velocity can be derived from CTD data using the geostrophic approximation and calculating the dynamic height of the water column relative to some level of no motion. This procedure is described below.

A. DATA COLLECTION

1. Pegasus

Pegasus casts were made at seven locations along the Point Sur transect, each spaced about 10 km apart, starting 33 km from the coast and finishing 100 km offshore (Figure 1). Each cast extends from the surface to the bottom. The stations were surveyed twice, with approximately 10 hours between casts, in order to later facilitate the elimination of inertial oscillations (at this latitude the inertial period is about 20 hours). Each cast actually yields two independent profiles - an upcast and a downcast - which can be analyzed separately or combined into an average profile. Therefore a total of 28 vertical profiles were collected by Pegasus. The details of the Pegasus station survey are given in Table 1.

The Pegasus instrument is an acoustically tracked velocity profiler which free-falls through the water column and returns to the surface after dropping weights on the bottom. The raw round-trip travel times of a 10 KHz signal sent by Pegasus and responded to by each of two bottom-mounted (and surveyed) transponders were recorded

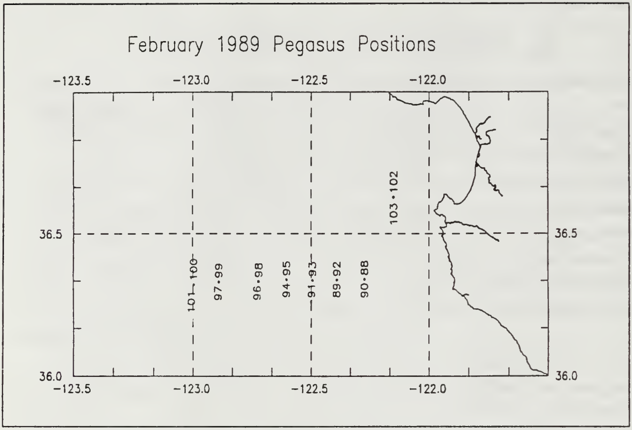

Figure 1. Pegasus cast locations along 36°20'N: station C1 (casts 88,90) is 33 km offshore. Station C7 (casts 100,101) is 100 km offshore.

internally. Travel times were later converted to distances using an average speed of sound. It was then possible to fix the path of Pegasus as it fell through the water column based on its consecutive positions and depths relative to the transponders. Velocities were derived from this path by differentiation with respect to time. The nominal fall and ascent rate for Pegasus on this cruise was 38 meters/minute and, with a ping every 16 seconds, velocities were recorded at about 10 meter increments. They are accurate to within about ± 1 cm/s, with uncertainties arising from assumptions regarding the speed and path of sound through the water column, as well as signal deformation and detection [Ref. 4].

Table 1. FEBRUARY 89 PEGASUS CASTS

Cast Sta#	Date Time	Location	Depth(m)
88 C1	2 3 11:16	36°20.39'N 122°16.41'W	1027
89 C2	2 3 16:07	36°20.19'N 122°23.49'W	1392
90 C1	2 3 21:26	36°20.47'N 122°16.43'W	982
91 C3	2 3 23:47	36°20.11'N 122°29.88'W	1872
92 C2	2 4 01:59	36°20.21'N 122°23.45'W	1388
93 C3	2 4 09:27	36°20.11'N 122°29.66'W	1882
94 C4	2 4 12:04	36°20.14'N 122°36.37'W	2694
95 C4	2 4 20:33	36°20.29'N 122°36.30'W	2664
96 C5	2 5 00:32	36°20.37'N 122°43.66'W	3235
97 C6	2 5 07:14	36°19.78'N 122°53.64'W	3438
98 C5	2 5 11:41	36°19.91'N 122°43.30'W	3152
99 C6	2 5 19:21	36°19.81'N 122°53.45'W	3373
100 C7	2 5 23:23	36°19.19'N 122°59.80'W	3286
101 C7	2 6 15:10	36°18.82'N 123°00.22'W	3308

2. ADCP

The *RV Point Sur* was outfitted with a RD Instrument DR0150 ADCP with a four beam JANUS array operating at a frequency of 150 KHz. ADCP data were collected continuously for the duration of the cruise. The mean of the approximately 200 individual pings received every three minutes was stored in one single data file (one vertical profile) representing that three minute period, and recorded onboard together with the ship's navigation data.

The accuracy of the ADCP is highly dependent on the quality of shipboard navigational data used to convert the relative velocities measured by the ADCP into absolute velocities, as well as the ship's speed, maneuvering (which compounds problems of gyro lag), and data collection intervals. All of this lends considerable uncertainty to the final velocities obtained. Kosro [Ref. 5] states accuracies of 4-5 cm/s in the U component, and 2-4 cm/s in the V component, relative to moored current meters. I believe the ADCP velocities used in this study are probably of about the same accuracy.

3. CTD

Twenty CTD stations were surveyed along the transect. Details of the survey are given in Table 2. CTD station 1 was located 3 km offshore, and CTD station 20 was about 140 km from the coast. CTD stations 7 through 18 corresponded roughly to

the geographic section covered by Pegasus stations C1 through C7, about 65 km in length. Figure 2 shows the location of all 20 CTD stations along the transect.

The Neil Brown Mk III CTD is considered to be accurate to within ±.005 PSU (salinity), ±.005°C (temperature), and ±3.2 dbar (pressure), with a resolution of .001 PSU, .0005°C, and 1.75 dbar. The instrument was lowered non-stop to the bottom once on station, then halted periodically during the upcast to collect water samples for later use in salinity calibration.

Table 2. FEBRUARY 89 CTD CASTS

Cast#	Date/Time	Location	Depth(m)
1	2/3 04:03	36°20.44'N 121°55.49'W	40
2	2/3 04:47	36°20.45'N 121°58.78'W	85
3	2/3 05:21	36°20.42'N 122°01.37'W	120
4	2/3 06:06	36°20.35'N 122°04.60'W	300
5	2/3 06:43	36°20.32'N 122°07.83'W	665
6	2/3 08:21	36°20.49'N 122°12.09'W	903
7	2/3 09:25	36°20.41'N 122°14.32'W	993
8	2/3 12:56	36°20.34'N 122°18.28'W	750
9	2/3 14:01	36°20.37'N 122°21.07'W	1185
10	2/3 16:31	36°20.04'N 122°25.69'W	1650
11	2/3 18:53	36°20.57'N 122°29.13'W	1886
12	2/4 05:01	36°20.06'N 122°33.00'W	2280
13	2/4 07:12	36°19.96'N 122°35.43'W	2620
14	2/4 15:08	36°20.00'N 122°38.89'W	3150
15	2/4 17:47	36°19.88'N 122°42.88'W	3190
16	2/5 05:12	36°20.02'N 122°48.90'W	3015
17	2/5 16:53	36°20.07'N 122°55.84'W	3300
18	2/6 00:50	36°25.14'N 123°01.99'W	3510
19	2/6 05:44	36°15.83'N 123°11.82'W	3350
20	2/6 10:22	36°07.23'N 123°28.97'W	3605

B. DATA PROCESSING

1. Pegasus

The raw Pegasus data were initially processed using programs written at the University of Rhode Island [Ref. 6] and modified for use at the Naval Postgraduate

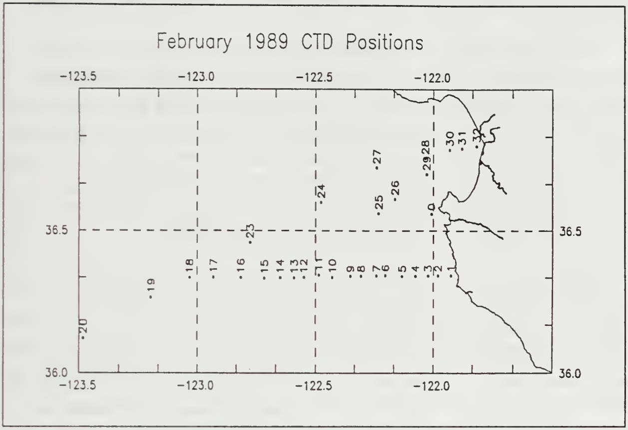

Figure 2. **Point Sur Transect:** these are the locations of CTD stations 1-20 along the transect.

School by Tarry Rago. Data were converted to velocities, which were hand-edited to remove obviously bad points, and then vertically filtered (to remove noise) using a 30 meter Hanning halfwidth. This resulted in four independent profiles for each Pegasus station, which could then be averaged together to obtain an average velocity profile at the station, with inertial effects partially removed.

2. ADCP

Detailed descriptions of the work necessary to convert the raw relative velocities measured by ADCP into meaningful absolute velocities are contained in Reece [Ref. 7] and King [Ref. 8]. For this study the profiles were averaged over 30 minutes (i.e. 10 profiles) and filtered vertically using a Hanning window with a 2 bin (8 meter) halfwidth. The reference layer (which is used as a baseline for converting relative to absolute velocities) chosen was 28-48 m, based on a "good ping" return of at least 95 percent in that layer. ADCP data were initially processed using programs written by Paul Jessen of the Naval Postgraduate School's Oceanography Department. Additional information re-

garding the processing of ADCP data and justification for averaging intervals is given by Kosro [Ref. 5].

The 30 minute average profiles were sorted by longitude to produce the vertical cross-sections in Chapter 3. This was necessary to accomodate the overlapping that occurred as a result of traversing the same track several times to revisit Pegasus stations (so that inertial oscillations could be averaged out of the Pegasus data). It is clear that the resulting cross-sections include data from several profiles near any particular geographic point that are not necessarily proximate in time. But since the major portion of the transect was revisited in this fashion, I do not feel overly concerned about the reliability of the resulting cross-sections with respect to this procedure.

3. CTD

Initial processing of the CTD data was conducted using programs written by Paul Jessen. The data were edited for bad points and averaged into 1 meter bins. Temperature and conductivity measurements were calibrated to water samples randomly collected at various depths and stations. After initial calibration, a substantial error still existed between (true) bottle values and "calibrated" salinity values in the CTD data file. To correct this discrepancy, CTD data were further adjusted using a polynomial least squares regression fit. A more complete description of this procedure is contained in Appendix A. Density was calculated from the calibrated CTD data using the 1980 equation of state, EOS 80, as presented by Fofonoff [Ref. 9]. Geostrophic velocities were then deduced by the "dynamic method" as described by Fomin [Ref. 10: pp. 68-78], assuming a balance between the pressure gradient and Coriolis forces.

III. ANALYSIS

This chapter will describe the data collected along the Pt. Sur Transect in February. An in-depth look at the data will present us with a comprehensive picture of the waters off Point Sur and, we hope, provide a meaningful addition to the body of knowledge, existent and future, on the seasonal characteristics of the area's currents. Velocity cross-sections are examined first, then correlations and comparisons between cross-sections. Finally the temperature, salinity, and density fields are inspected. Throughout this thesis standard notation shall be used to denote the three components of velocity: U for zonal flow (E-W), V for meridional (N-S), and W for vertical. Positive velocities are eastward, northward, and upward respectively. By our own convention, Pegasus stations will be prefixed by the letter C( ); CTD stations will be referred to by number only. Throughout this paper meters and decibars will be used interchangably, there being little difference at the depths considered.

A. VELOCITY CROSS-SECTIONS

1. Pegasus

a. V Component

The seven Pegasus stations constituted a geographic cross-section 65 km in length, from C1 (33 km offshore) to C7 (100 km offshore). A view of the entire water column (see Figure 3) shows details of several flow regimes. Poleward flow (the Davidson Inshore Current) was evident in the upper 1000 m as far as 75 km offshore (station C5). This current was strongest at the surface, (more easily seen in Figure 4) with a 10 cm/s isotach extending to 300 m, and a core maximum of 26 cm/s down to 25m. The flow was much stronger than that suggested by Chelton [Ref. 1], who claimed a maximum of 14 cm/s in December and a mean February value of less than 5 cm/s. The offshore boundary of the coastal jet was about 50 km from the coast. The inshore flow was not resolved by Pegasus (C1 is 33 km offshore).

There appear to be two distinct equatorward regimes. The first was a loosely defined and weak (less than 5 cm/s) southward current which was the predominant feature of the flow farther offshore. From about 60 km out, the surface flow was largely to the south; this was the California Current (CC). With the exception of an incursion of very weak poleward flow between 200-500 m, the CC extended to a depth of 1000 m. A

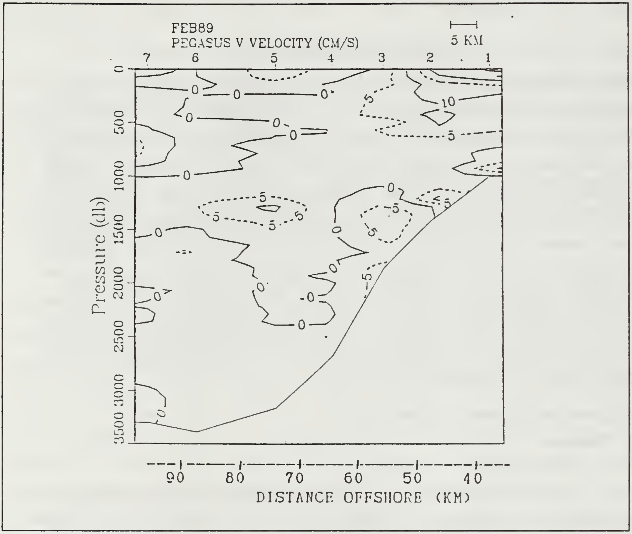

Figure 3. Pegasus cross-section of V (0-3500 m): meridional (N-S) velocity component. Positive values indicate poleward flow, negative values equatorward flow. Stations (C1 thru C7) are indicated along the top. C1 is 33 km offshore, C7 is 100 km offshore. Contour interval is 5 cm/s.

very weak equatorward flow resumed below 1500 m, but this was related to the equatorward flow over the slope region farther inshore.

The second area of significant southward flow was over the entire slope region (stations C2-C5). This flow was also weak, less than 5 cm/s, but it was very well defined. This current hugged the slope, and was generally found within 500 m of the bottom along the slope, with good vertical separation from the stronger poleward current that lay above it. It was the counter-current to the surface poleward flow of the Davidson Inshore Current. Over the coastal rise (75-100 km offshore), the equatorward

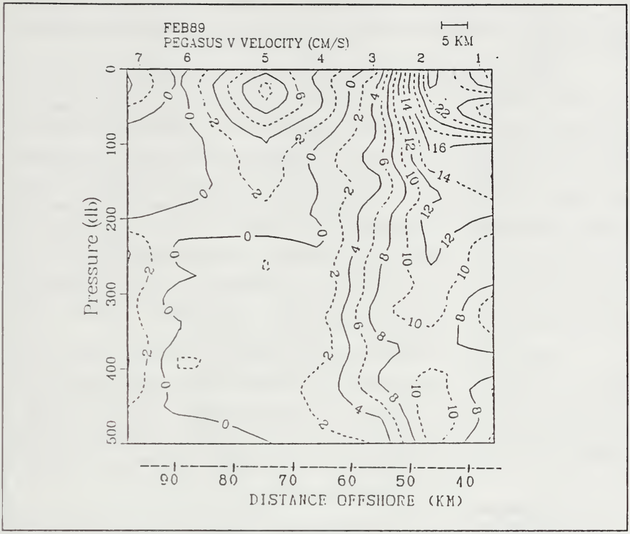

Figure 4. Pegasus cross-section of V (0-500 m): meridional (N-S) velocity component. Positive values indicate poleward flow, negative values equatorward flow. Contour interval is 2 cm/s.

flow extended from the bottom up to 1500 m; in fact one could say that the bottom slope current was generally found below 1500 m.

An interesting feature of the outer shelf region was the deep southward jet at C1, hereafter referred to as a trench jet. Located 33 km from the coast, just shoreward of an extensive topographic ridge which rises 200 m above the continental slope, this 200 m thick core of water flowed southeast through a depression between the continental slope and the ridge offshore, filling the depression. The southward current at this time of year (-12 cm/s) was in contrast to the strong northeast flow observed here during the long upwelling season [C.A. Collins, pers. comm.], and appears to be a topographically steered phenomenon. It is perhaps related to winter flow out of the Monterey Canyon;

when the undercurrent is deep and strong during the summer and fall, bottom currents through this gap may meander into the canyon to balance in part the offshore surface Ekman transport.

There is also the possibility that the trench jet was not carrying water out of the canyon, but simply recirculating water from further offshore around the ridge 35 km from the coast. If it were conserving potential vorticity, it could be topographically trapped around the ridge. An investigation of the temperature and salinity characteristics of the water in the trench (900 m) reveals that water of the same T/S could come from further offshore. If it came from CTD station 9 (45 km offshore), which is just west of the ridge, it would have to be displaced vertically only 38 m - i.e. water of the same T/S characteristics exists 38 m deeper west of the ridge. If on the other hand the trench jet water was coming from even further offshore (CTD station 10, 53 km from the coast), it would only have to be displaced vertically 10 m (i.e. water of similar T/S 20 km west of the ridge is found 10 m shallower than the water in the trench).

Lastly, I focus on two well-resolved features of the upper ocean (see Figure 4). The first was a narrow surface equatorward jet of moderate strength (10 cm/s) located 65-80 km offshore (near C5), extending to a depth of 100 m. The other feature was the strong horizontal shear zone between C2 and C3, approximately 40-50 km offshore. Here V decreased from 24 to 4 cm/s over a horizontal distance of only 8 km.

b. U Component

From Figure 5 one can see three distinct flow regimes in the zonal velocity U. First, there was a broad westward surface current, intensifying inshore, which extended down to the upper slope (1800 m) but was shallower over the deep ocean (400 m). Underlying this there is a broad and weak onshore flow. Finally, there was again a weak offshore current centered over the outer slope and rise, from the bottom to about 1800 m (C4-C5). It is possible that the two offshore ($U < 0$) regimes were connected (the weak velocities here are barely within the precision of the instrument), but this cannot be resolved by Pegasus station spacing. As with V, it is immediately apparent from Figure 5 that apart from the surface layer, flow was extremely weak throughout the region, with currents less than 5 cm/s. The trench jet appeared to have a weak (< 5 cm/s) onshore component, in contrast to the generally westward flow of the entire water column out to C3.

Near-surface flow exhibits more structure and significant velocities. Looking at the upper 500 m in finer detail (Figure 6) we see two centers of offshore flow at the

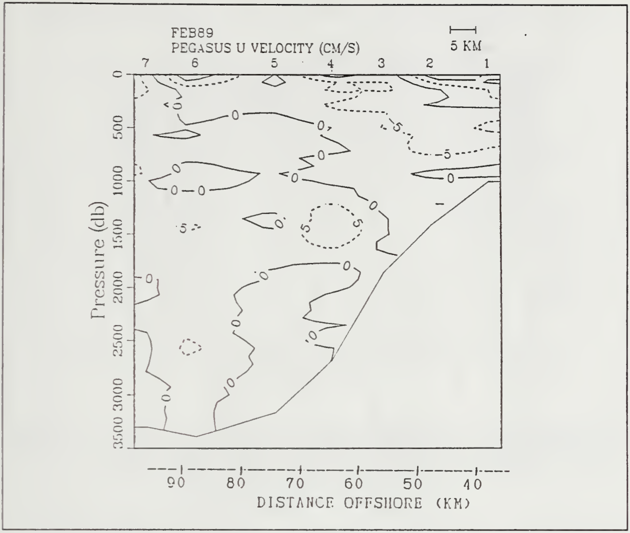

Figure 5. Pegasus cross-section of U (0-3500 m): zonal (E-W) velocity component. Positive values indicate onshore flow, negative values offshore flow. Contour interval is 5 cm/s.

surface. The strongest, found inshore, had a core velocity of 25 cm/s to the west. The -10 cm/s isotach extended down to 300 m over a 20 km stretch from C1 westward (eastern boundary unresolved by Pegasus). The core (> 20 cm/s westward) was shallow, only 40 m deep. The other offshore flow core was centered at C6 (90 km offshore), but it was much weaker with a core velocity of only 12 cm/s. Shear zones existed 45-55 km and 95-100 km offshore, although cross-shelf shears were not as strong as those in the V component.

2. ADCP

While better horizontal resolution was achieved in the ADCP cross-sections, they were limited in coverage to the upper 300-400 m of the water column. The ADCP

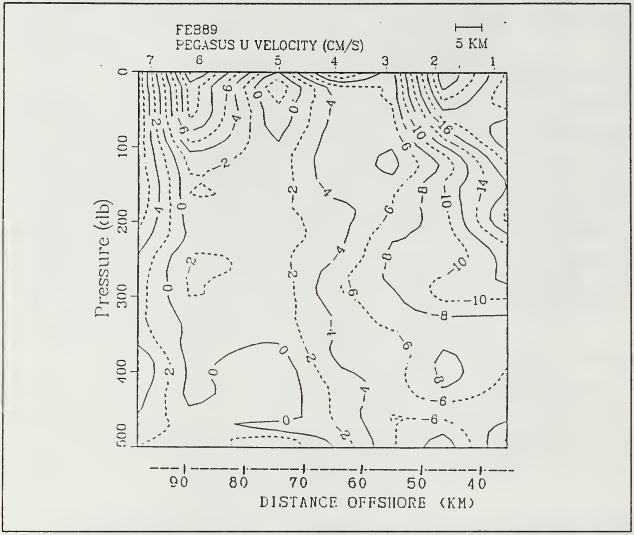

Figure 6. Pegasus cross-section of U (0-500 m): zonal (E-W) velocity component. Positive values indicate onshore flow, negative values offshore flow. Contour interval is 2 cm/s.

profiles discussed here varied in their vertical extent between 250-450 m. For the purposes of this study, a cut-off depth of 300 m was chosen both to maximize the number of usable profiles and to eliminate deeper values where the ADCP was at its operational limit. The top and bottom 10-20 meters have been lost in the filtering and contouring routines. As we have already seen, most of the structure of the California Current is in the top 300 m, so we are able to make important comparisons between Pegasus, ADCP, and CTD cross-sections. The ADCP sections cover a 140 km track from the coast to CTD station 20.

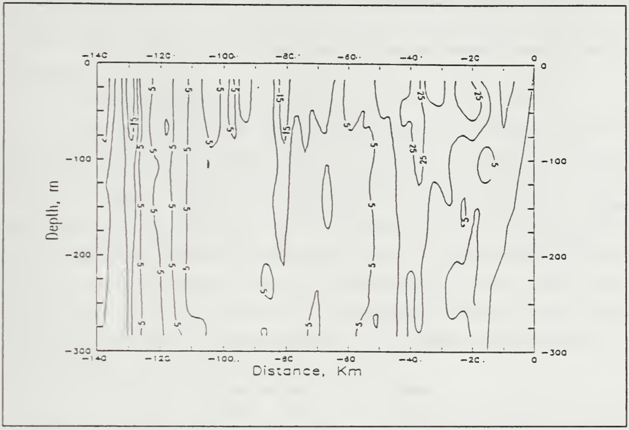

Figure 7. ADCP cross-section of V (15-290 m): meridional (N-S) velocity component. Positive values indicate poleward flow, negative values equatorward flow. Contour interval is 5 cm/s.

a. V Component

The ADCP V component is shown in Figure 7. Many similarities between this and the Pegasus sections are noted. The major features agree quite well both in geographic location, intensity, and depth. The strong poleward flow at the surface inshore (the Davidson Inshore Current) is very recognizable. The current was most intense at the surface (25 cm s), from 20-40 km offshore, and the core extended down to about 100 m. The shear zone at about 60 km, where the velocity changes sign, is consistent with Pegasus data, which show the (V = 0) line about 57 km offshore. A moderate equatorward current on the surface at 75 km was also evident, with a velocity of about -10 cm s, imbedded in the weak southerly flow from 60 km out. This jet had a core 30 m below the surface, and was well resolved in both the Pegasus and ADCP sections.

b. U Component

The cross-section of the ADCP U component (Figure 8) shows a very well-defined jet of offshore flow 30 km from the coast at 100 m. The strongest offshore

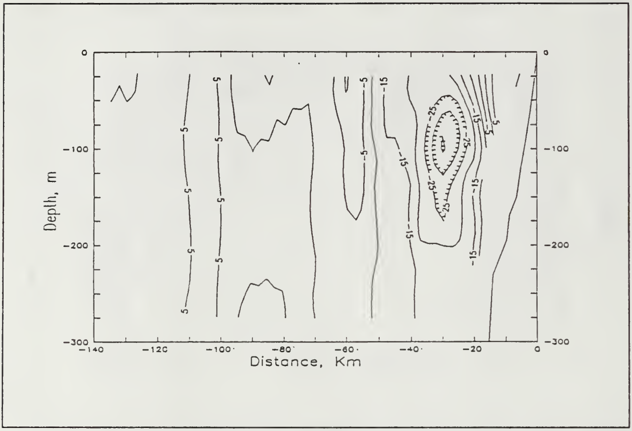

Figure 8. ADCP cross-section of U (20-280 m): zonal (E-W) velocity component. Positive values indicate onshore flow, negative values offshore flow. Contour interval is 5 cm/s.

flow was confined to the surface layer, but a distinct subsurface maximum is evident. The core velocity was -35 cm/s, and the -25 cm/s isotach extended from 60 m to 180 m. This feature was not present in the Pegasus section at C1 (33 km), where it should be evident. The two sections of cross-shore velocity looked at thus far agree well, however, in that the offshore flow is significantly stronger near the coast, and are roughly consistent in magnitude (20-30 cm/s).

It should be noted that the surface winds were from the southwest at 5 m/s until about 1200 GMT on 4 February, then veered to the northwest and strengthened to 10 m/s through the fifth, and later veered to the north, all in conjunction with the passage of a cold front which left snow on the coast. The southerly wind stress early in the cruise, corresponding to the eastern portion of the transect, would not result in offshore transport. Additionally, the fact that the offshore flow has a subsurface maximum does not reflect Ekman dynamics, which would result in surface intensification of the flow (at the friction source). This leads me to suspect the submerged core of westward

flow was a result of convergent currents near the coast, creating an offshore squirt which had little connection to the wind stress at the time. The nature, source, and geographic location of such subsurface convergence is not resolved by this study, and thus remain conjecture.

3. Geostrophic Currents

Since the Point Sur transect is oriented east/west, geostrophic velocity based on CTD data is available only for the V component. Additionally, it should be understood that while the major portion of the transect is along 36°20'N, the final 40 km (from CTD station 18 to 20) is along a line which angles 30 degrees to the south. Several geostrophic cross-sections are examined here, each with a different "level of no motion" (LNM). First we shall examine velocity sections based on assuming the LNM to be the deepest common point between stations (in effect the bottom). These results are then compared with geostrophic V calculated for more empirically-determined (from Pegasus) LNMs (500 and 1000 m). Where the water is shallower than the LNM chosen, a default to the deepest common point is employed.

a. LNM at deepest common point between stations

The Davidson Inshore Current, with a maximum core of about 20 cm/s about 40 km offshore (near CTD station 8), is seen in Figure 9. This agrees quite closely with the Pegasus results (Figure 4) of 24 cm/s at 42 km. There was, however, a confused 45 km wide shear zone in the geostrophic cross-section which was not present in either the Pegasus or ADCP data. The transect from CTD stations 11-17 has alternating bands of positive and negative V from -10 to 15 cm/s. This shear zone extends down to 1500 meters. Deeper flow is uniformly weak (less than 5 cm/s). One possible explanation for this banding is the presence of a first mode internal wave. Examination of the 7.5°C isotherm in Figure 12 suggests definite wave structure at 250-300 m. A first mode internal wave would produce a quasi-barotropic response throughout the water column, which would account for the densely packed, vertically coherent bands of alternating flow. The wavelength indicated by the temperature plot is about 20-30 km, which corresponds fairly well to the distance between one full reversal of V. It is difficult to account for the fact that this feature is not reflected in the ADCP cross-sections, since it is well within its' resolution. As we shall see in the next section, the banding area can be altered in terms of depth and intensity by changing the LNM. The resulting cross-sections will be examined to see if they are more consistent with Pegasus and ADCP sections.

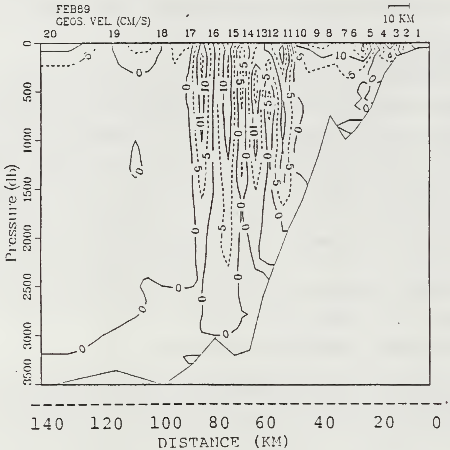

Figure 9. Geostrophic velocity(3500 m): LNM is the deepest common point between adjacent stations. Note the 200 m ridge present at station 8. Contour interval is 5 cm/s.

An interesting feature of Figure 9 is the narrow jet of equatorward flow just inshore of the Davidson Inshore Current (stations 2-5). This core of water (-10 cm/s) is about 12 km wide and occupies the entire water column over the shelf break. It is surrounded by poleward flow (stronger on the seaward side) and extends at least 150 m. The DIC is generally thought to extend laterally to the coast, and the ADCP indicates no such inshore "counter-countercurrent". It is likely this feature is not real and results from geostrophic assumptions which are not correct. In shallow water, frictional effects and wind forcing can cause substantial deviations from geostrophy. Additionally, problems arise from extending a LNM into the shallow coastal water.

Looking at Figure 9 we see that while the broad equatorward flow of the California Current was present offshore of station 17 to a depth of 2500 m, there was a poleward geostrophic velocity below that which was not confirmed by the Pegasus data (Figure 3).

Lastly, we see that the trench jet mentioned earlier in the Pegasus section (Figure 3) is present in the geostrophic section as well. The core velocity has been slightly reduced, however, from 10 cm/s to less than 5 cm/s.

b. LNM at 500 meters.

Most of the previous studies of the California Current, including Chelton and Lynn [Refs. 1,11], have used 500 m as an assumed level of no motion. As can be seen in Figure 3 this is a reasonable approximation except in the nearshore region of the DIC, where currents greater than 5 cm/s are found at that level.

The most striking change in the geostrophic cross-section using 500 m as the level of no motion (Figure 10) is the vertical displacement of the banded shear zone (55-90 km offshore). Instead of being the dominant feature of the upper water column (above 1500 m), imposing a shallower LNM has shifted the shear down to the bottom. In fact there is no trace of it above 1000 m. This suggests that the internal wave alluded to earlier as a possible mechanism for the shear is not the cause, for if a shallow (above 500 m) internal wave was responsible for the shear zone, the bands would still remain above 500 m. Now that the upper water has been "purged" of the bands, and they are most intense along the deep outer slope and rise, a new explanation is necessary. It seems most likely that the bands are artifacts, arising from a variable LNM relating to the scale of the density fluctuations and station spacing. If they are real (and it is impossible to confirm this based on the horizontal spacing of Pegasus data), they could be topographic waves or internal waves reflecting off the sloping bottom.

c. LNM at 1000 meters

There is good justification for choosing 1000 m as a level of no motion. Except for the trench current at C1, the 1000 dbar level is the best overall candidate for that designation based on Pegasus data. Below 1000 m one runs into the broad equatorward bottom flow. It is also the level which separates the inshore countercurrent from the equatorward slope regime. In the U component as well (Figure 5) there is negligible flow below 1000 m. One would expect a geostrophic velocity cross-section based on the 1000 m LNM to be more accurate than one based on the deepest common point, since the current speed is closer to zero in the mid-water region.

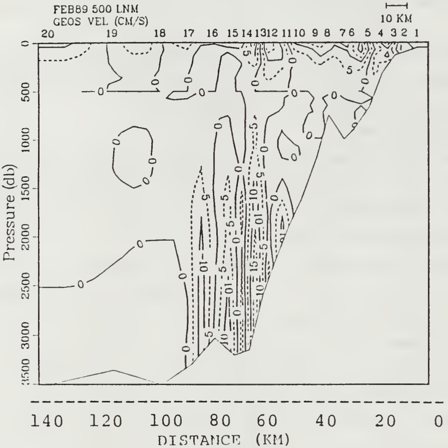

Figure 10. Geostrophic velocity (0-3500 m): meridional (N-S) velocity component. Level of no motion is 500 m. Positive values indicate poleward flow, negative values equatorward flow. Contour interval is 5 cm/s.

Looking at Figure 11 we see that the intensity of the shear bands has been significantly reduced. The other major features are not much affected by a change in the LNM. The intensity of the Davidson Inshore Current remains the same (< 25 cm/s). The trench jet is present at station 6, consistent with the Pegasus section, though somewhat weaker (< 5 cm/s to the south).

In summary, I conclude that the 1000 m level of no motion applied to the CTD data produces the most accurate representation of geostrophic currents. This is based on the structure and magnitude of the near-surface features, and the fact that the shear zone is reduced in intensity and limited in extent to the bottom 1500 meters. More work is necessary in order to determine whether or not the banded shear zone is a real

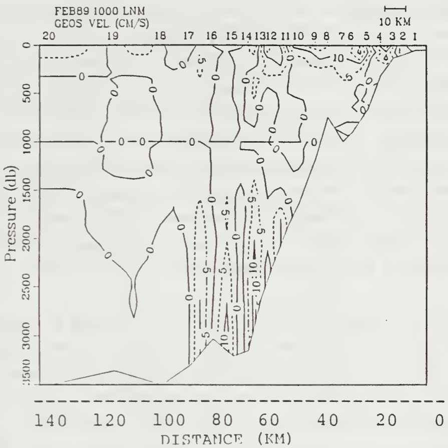

Figure 11. · Geostrophic velocity (0-3500 m): meridional (N-S) velocity component. Level of no motion is 1000 m. Positive values indicate poleward flow, negative values equatorward flow. Contour interval is 5 cm/s.

feature, and if so to more closely examine it. As we shall see in the density section below, there is a wave structure to the deep isopycnals that would support some velocity shear in the bottom water between CTD stations 10-17.

B. TEMPERATURE

One can see from a temperature field derived from CTD data (Figure 12) that the Davidson Inshore Current was about .5°C warmer than the surrounding equatorward flow. This region of warmer temperature correlates well with the region of higher velocities. The sloping isotherms indicate downwelling and poleward flow along the upper

slope and shelf to 750 m. In addition, there seems to be a wave-like structure to some of the isotherms, particularly the 7.5°C isotherm as mentioned earlier.

Three temperature profiles are seen in Figure 13, collected from stations 6, 14, and 20. We note how the mixed layer deepens as we move offshore, from 10 m at station 6 (the core of the DIC), to 30 m at station 14, and to 80 m at the far end of the transect. To better see relative temperature differences along the transect, Figure 14 shows how the station profiles compare with station 20, furthest offshore. In this figure, I have subtracted the temperature at station 20 from the temperature at corresponding depths at every other station, thus producing a cross-section of relative temperature. It is easier to visualize certain features of the temperature field in this manner, such as the warm Davidson Inshore Current. The water on the shelf break (80-150 m) was also warm, an indication of its subtropical origins. It is clear that the deeper mixed layer (80 m) at station 20 is responsible for the long anomalous cold layer from 30-80 m seen in Figure 14.

The sea surface temperature of about 11°C over the entire area was anomalously cool, as indicated by Figure 15. The central California coast was witness to an unusual cold air outbreak during this period. The composite average sea-surface temperature for this season at Granite Canyon, close to Point Sur, is about 12.5°C. Comparisons with temperature sections collected during prior cruises [e.g. Ref. 7] indicate that the cooler than normal surface temperatures did not affect the water below 100 m. The 9.5°C isotherm is typically located at about 100 m depth, in agreement with the data presented here. February. The thermocline was substantially weakened, however, by the cooling of the surface waters by about 2 degrees.

C. SALINITY

It has long been observed that salinity in the California Current increases with depth. This can be seen clearly in Figure 16. But the fact that the Davidson Inshore Current manifests itself as a salinity minimum is a surprise, considering the subtropical origins of the poleward undercurrent, which is supposedly the progenitor of the Davidson Inshore Current. It also contrasts with the observations of Chelton [Ref. 1], Lynn [Ref. 11], and others who have noted a salinity maximum in the poleward undercurrent. The reason for this salinity minimum in the poleward flow is not clear. It could be explained by an intrusion further south of fresh river runoff, captured and concentrated by the relatively fast flow of the Davidson Inshore Current. However, this is not likely, as there are few potential land sources for the runoff. Perhaps more likely is the

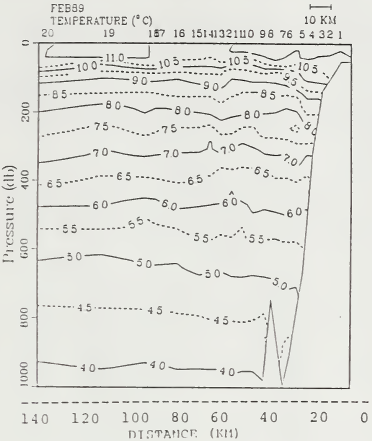

Figure 12. CTD Temperature (0-1000 m): the temperature field along the Point Sur Transect. Contour interval is .5°C.

existence of a low salinity source further offshore being advected into the region, or even a recirculation of fresh water discharged further north. Values of less than 33.5 PSU are recorded in the surfaced core of the poleward flow. A local salinity maximum (33.6 PSU) is apparent at the surface between stations 11-14, indicative of upwelling. This could be the result of local divergence produced at the surface by the intensified offshore flow at C4 (Figure 6).

A wave-like structure is apparent along several isohalines, especially 34.0 and 34.3, similar to that seen in the temperature section, and corresponding roughly in depth (200-250 m and 550-600 m). The length scale of the disturbance (20-30 km) is once again suggestive of internal waves.

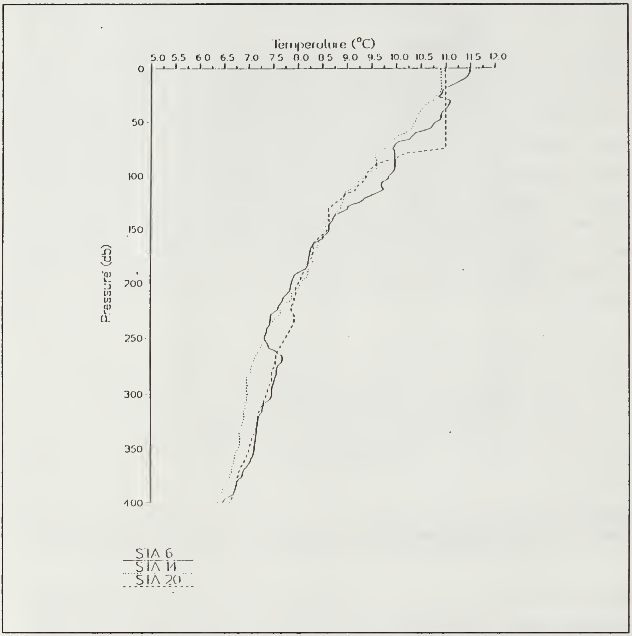

Figure 13. Temperature profiles from 3 CTD stations (°C): profiles from CTD stations 6,14,20 indicate how the mixed-layer deepens further offshore.

D. DENSITY

Here I examine the density structure of the transect as it was calculated from the CTD temperature and salinity data. What I refer to in the following discussion as density is actually the density anomaly (γ) referenced to atmospheric pressure. The values are very close to sigma-t. For a more complete explanation of γ the reader is referred to UNESCO [Ref. 12]. A look at Figure 17 reveals the isopycnals sloping in a direction

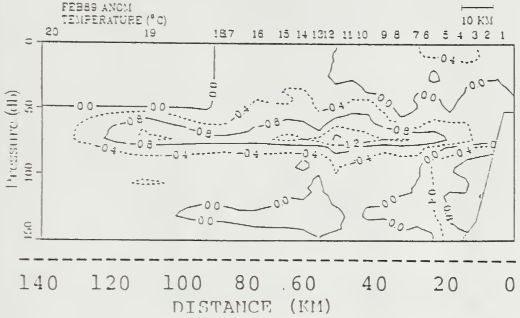

Figure 14. Temperature anomalies(°C): the temperature field as seen by CTD is normalized by the temperature profile at station 20. The long band of negative temperature anomaly from 50-80 m is due to the fact that the mixed layer deepens further offshore. Contour interval is .4°C.

consistent with the geostrophic flow of both the California Current and the Davidson Inshore Current. The poleward surface jet was a density minimum, as one would expect from a current distinguished by warm, fresh water. Values at the core were less than 25.5 kg m^3, with the 25.6 isopycnal extending 40 km across the jet. A local maximum of density was present at CTD station 14, with density surfaces bulging upward due to the corresponding salinity maximum at the surface.

The density cross-section in Figure 18 covers the 45 km portion of the transect between CTD stations 10-17. This is the area in which the banded shear zones were evident in the geostrophic velocity cross-sections, and is the outer edge of the continental mar-

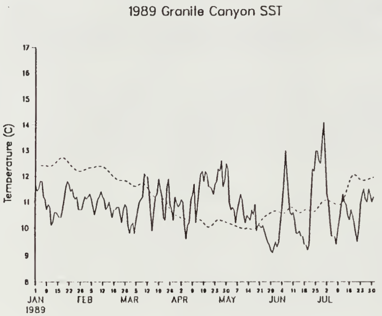

Figure 15. **1989 Granite Canyon SST(°C):** sea-surface temperatures observed at Granite Canyon (near Point Sur. Solid line is 1989; dashed line is 15-year average.

gin. By examining the density structure closely (the contour interval is .02kg/m³), one can see a definite wave-like pattern in the deep isopycnals. The 27.70 and 27.52 isopycnals have a pronounced wave structure, on a scale of about 20 km. The most striking feature of this figure, however, is the severe slope of the 27.74 isopycnal at the very bottom, located just at the base of the continental rise. The alternating slope of this density surface is large enough to cause the alternating geostrophic velocity shears at the bottom seen earlier, and support the bottom-intensification of those shears, as indicated by Figure 11.

A look at several individual density profiles (Figure 19) from CTD stations 2-6 indicates that density increased shoreward, yielding the equatorward geostrophic velocity

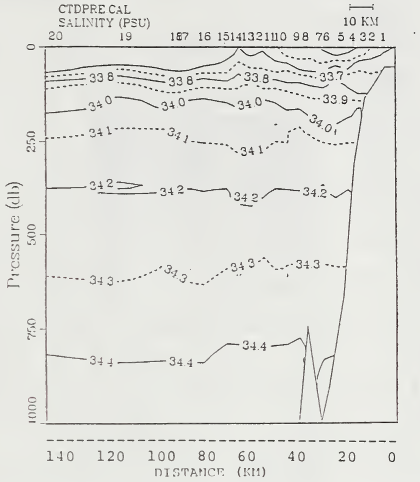

Figure 16. · Salinity cross-section of Pt. Sur Transect: contour interval is .1 PSU

component derived earlier. The fact that the flow was poleward (indicated by ADCP) means this flow may have been dominated by barotropic pressure gradients or was wind-driven.

E. INFRARED IMAGERY

An infrared image obtained from the NOAA-11 polar-orbiting satellite at 2330 GMT on 5 February 1989 (Figure 20) shows the northwest-southeast structure of the sea-surface temperature gradient in the coastal waters off Point Sur. This provides some evidence of the northwest flow of the Davidson Inshore Current. The warmer temperatures near the coast (10-60 km offshore) associated with this current are also clearly indicated by the darker area extending from the south up to the mouth of Monterey Bay. The warm water from the Southern California coast can be seen to meander its way

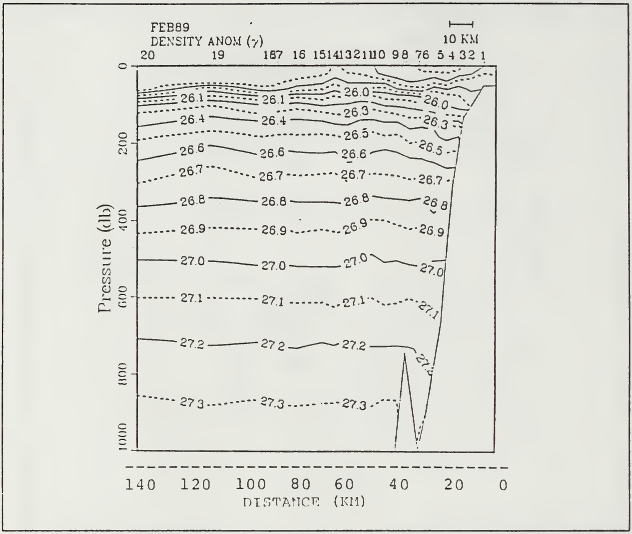

Figure 17. Density anomaly (γ) cross-section of Pt. Sur Transect: contour interval is .1 kg m³.

north, cooling significantly as it proceeds up the coast. The front which delineates the warm waters off Point Sur is aligned northwest-southeast; off Monterey Bay this front turns anticyclonically to the northeast and east, but the warmer surface waters do not actually reach in to Santa Cruz. This water then penetrates northward, almost to Point Reyes. A large warm eddy, its western edge obscured by cloud cover, is present about 200 km west of Monterey Bay. These warm offshore waters are connected to the warm water north of Point Reyes by a weak warm anticyclonic tongue of water. These warm waters north of Point Reyes are kept separate from the warmer waters to the south by a cold filament which originates at the coast near Point Reyes. The details of the image

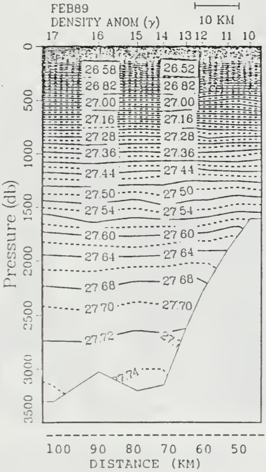

Figure 18. **Density anomaly (γ) cross-section:** this section covers CTD stations 10-17, corresponding to the banded shear zone. There is considerable wave structure in the deep isopycnals, especially 27.70. Note the severe slope of the 27.74 isopycnal at the bottom, which supports the large (10-15 cm s) geostrophic velocities evident in the earlier figures at the bottom. The contour interval is .02 kg m^3.

(including the absolute temperatures) cannot be investigated more thoroughly due to problems with image calibration.

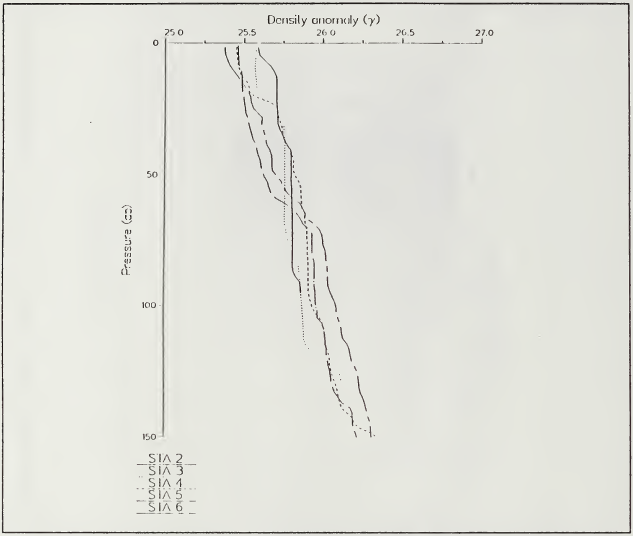

Figure 19. Density anomaly (γ) profiles: units are kg/m^3. Shown are 5 profiles from CTD stations 2-6, along the shelf (5-30 km offshore). Note how near-surface densities are larger inshore, supporting equatorward geostrophic flow just east of the DIC (as is Figure 9).

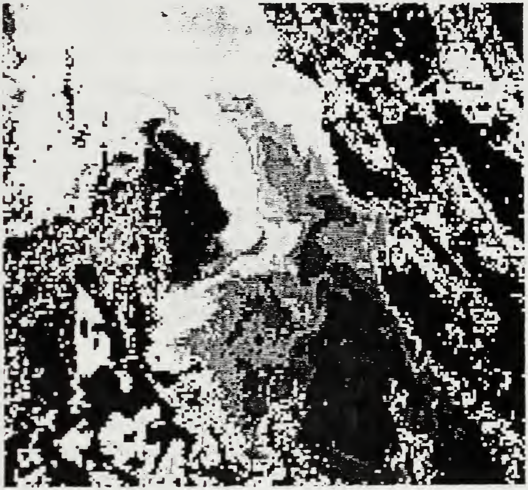

Figure 20. Satellite IR image of California coast: NOAA-11 (channel 4) sea-surface temperature field on 5 February 1989 at 2330 GMT. The Central California coast and offshore clouds are black. Monterey Bay is in the center of the image. Darker shades indicate warmer temperatures; lighter shades are cooler SST. The temperature difference between successive gray shades is believed to be .5°C. The DIC is manifested by the stream of warm water flowing northwest off Point Sur about 10-60 km from the coast.

IV. CONCLUSIONS

A. OCEANOGRAPHY

The California Current system off Point Sur in February was found to consist of two prominent flow regimes and several smaller, though interesting, features. The California Current was a weak (< 5 cm/s) and fairly deep (> 2000 m) equatorward flow found at least 90 km offshore. Surface-intensified, it was present closer inshore (60-90 km), but only in the top 200 m. In general, this current was highly geostrophic, based on CTD data. The Davidson Inshore Current, or surfacing of the poleward undercurrent, was stronger (25 cm/s), also surface-intensified, and extended down to 500 m. It was characterized by warm, fresh water and a shallow (or nonexistent) mixed layer. The salinity minimum at its core contrasts with earlier studies showing it as a salinity maximum. The reason for this salinity minimum is not clear. The Davidson Inshore Current was also largely geostrophic.

In addition to the two main currents, there were clear indications of an equatorward bottom slope flow and a topographically steered trench jet. The bottom slope flow was constrained to the lower 500 m, and was strongest (> 5 cm/s) over the inner slope (45-65 km offshore). It appeared to be either a response to the strong poleward jet lying above it, or more broadly connected to the main equatorward flow further offshore (the California Current). It was impossible to determine whether this deep slope flow was geostrophic because of a 55 km-wide band of alternating shears at this location in the geostrophic cross-sections. A trench jet, supported by geostrophy, existed just inshore of a 200 m ridge located 35 km off the coast, and could represent deep southeastward flow out of Monterey Canyon. However, the water in the trench jet could just as well have been recirculated from further offshore, based on an analysis of T/S characteristics. The evidence is inconclusive as to which of these mechanisms might account for the trench jet. The flow inshore of the Davidson was poleward as well, contrary to geostrophy, suggesting other forces (friction, wind) dominate this flow regime.

B. INSTRUMENTATION

There appeared to be good correlations between the velocity profiles produced by the three different instruments. The main features, and regions where the flow exceeded 5 cm/s, agreed well both in intensity and spatial extent. Where the flow was weaker than 5 cm/s, considerable variations occurred, largely due to the fact the instruments had

reached their accuracy limits. The ADCP is useful as a location/intensity check on the other two instruments, as well as providing the only true velocities closer inshore. The Pegasus data, though sparse, are probably the most reliable and provided the best full-depth "calibration" to the CTD-derived geostrophic velocities. There is no doubt that using such a combination of diverse yet mutually-compatable instruments holds the most promise for further studies like this one.

Using the Pegasus cross-sections to determine a most suitable "level of no motion" (LNM) met with limited success, and is probably the most effective method of adjusting the geostrophic cross-sections at present. Based on a comparison of three different LNMs, I conclude that the 1000 m level is probably best in terms of the overall quality of the section produced, although it is far from perfect. Given a choice between the 500 and 1000 m levels, not much difference was noted in the upper ocean, where most of the interesting features are located, because 1) the currents are stronger there, so the error is a smaller fraction of the total flow, and 2) the most reasonable choices for a LNM (bottom, 1000 m, 500 m) are significantly below the stronger surface regime.

C. RECOMMENDATIONS

There were problems associated with choosing a level of no motion. As one might expect, in reality there is no such constant depth level, particularly in shallow coastal waters heavily influenced by topographic and frictional effects. Further, since the flow is never purely geostrophic, the accuracy of a geostrophic velocity cross-section relative to an actual velocity cross-section cannot be determined by a simple comparison between the two, since the latter contains non-geostrophic effects and will always be different from the former. Perhaps the best scheme might be to use a varying level of no motion, based on Pegasus, to baseline the CTD sections.

Further study is required to determine the cause and nature of the shear zone evident in the geostrophic cross-sections at the base of the slope (55-100 km offshore). It could be an artifact of the methods and assumptions used in the geostrophic relationship, yet this type of shear shows up in many studies of this kind, and no explanation is available. The bands may be an artificial product of the CTD station spacing, instrument accuracy, or computing routines. It is possible that the deep shear structure at the base of the slope is real, but most likely this will only be adequately resolved by moored current meters. If it is determined, or seems likely, that the shear zone is not real, it might be possible to eliminate it by horizontally averaging the geostrophic cross-sections. This would, however, lead to a loss of detail in the cross-sections.

Studies of the Point Sur Transect contribute significantly not only to our increasing knowledge of the oceanic region near our coast, but to a broader understanding of and appreciation for coastal processes in general. As such, they should be continued to allow for better verification of coastal models. The Navy shall have a continuing interest in this area in so far as such studies impact on undersea operations.

APPENDIX . SALINITY POST-PROCESSING

Upon processing the CTD data it became apparent that the post-cruise salinity calibration technique based on numerous bottle samples was yielding unsatisfactory values. The conversion of conductivity to salinity did not produce the same salinity values obtained by measuring water samples in the lab. An analysis of the true values versus the measured values indicated that a simple linear correction would not apply. An overvaluation of the measured data relative to the true data became greater with increasing salinity. A third-order polynomial regression was carried out to fit a curve to the data, as in Figure 21. However, since the domain of interest (33-35 PSU) was so small, the only way to effectively use a third-order polynomial to convert measured values to true values was to "zero" the data first, so it wouldn't blow up near the origin. The procedure, then, was this: 1) subtract a safe lower limit (33.4 was used) from the measured values in the CTD data file, 2) plug the results into the polynomial, and 3) add the constant (33.4) back to obtain corrected values. The results can be seen in Table 3. Prior to correction, errors of .04-.06 PSU were common. After this procedure, the average error (residual) was -.0035 PSU, which is less than the nominal accuracy of the CTD ($\pm$.005 PSU). A total of 42 bottle samples were used in this procedure, collected from a variety of depths and stations.

It is clear that this procedure cannot be used to extrapolate beyond the range of observed salinity values, and to do so using such a contrived and artificial technique (arbitrary constants?) would be to invite disaster. The author was careful in choosing legitimate limits, and wouldn't dare extrapolate beyond them.

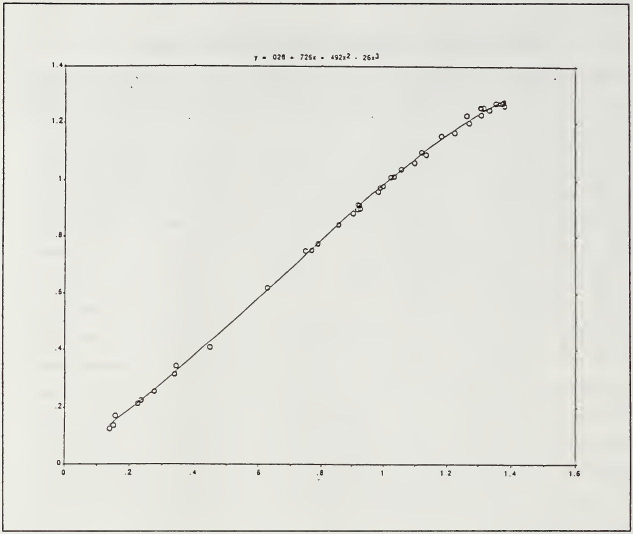

Figure 21. Polynomial regression fit to data: X is uncorrected salinity; Y is true salinity.

Table 3. **POST-CRUISE SALINITY CALIBRATION:** "Uncorr" are the raw values in the CTD data file; "Corr" are the same data after an O(3) polynomial regression is conducted; "True" are the actual salinities as measured from bottle samples in the lab.

Station	Depth(m)	UncorrSal	CorrSal	TrueSal	Resid
1	44	33.676	33.658	33.656	-.003
2	90	33.738	33.718	33.716	-.002
3	125	33.850	33.829	33.810	-.019
4	304	34.148	34.136	34.151	.015
5	656	34.325	34.313	34.301	-.012
6	292	34.168	34.156	34.153	-.003
7	982	34.499	34.473	34.462	-.011
8	729	34.387	34.372	34.374	.002
9	1171	34.536	34.504	34.490	-.014
10	1606	34.627	34.577	33.566	-.011
11	605	34.319	34.307	34.313	.006
11	1185	34.671	34.610	34.602	-.007
12	2273	34.709	34.636	34.629	-.007
13	2	33.558	33.552	34.571	.019
13	2509	34.735	34.653	34.648	-.005
14	3142	34.775	34.679	34.670	-.008
15	606	34.323	34.311	34.311	.000
15	3005	34.770	34.676	34.668	-.007
16	2505	34.716	34.641	34.655	.015
17	3292	34.780	34.682	34.662	-.019

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